AIR WAR COLLEGE

AIR UNIVERSITY

THE COMPLEXITY-ADAPTABILITY PARADOX:

ISSUES FOR COMBAT AIRCRAFT DEVELOPMENT

by

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Biography

Lieutenant Colonel Michael Norton is currently assigned as a student of the Air War College, Maxwell Air Force Base, Alabama. He entered the Air Force in 1991 at Sheppard Air Force Base, Texas where he completed Euro-NATO Joint Jet Pilot Training. Prior to attending the War College, Lieutenant Colonel Norton served continuously for fourteen years as an operational F-16 pilot and instructor in the Regular Air Force and the South Carolina Air National Guard. During his career, he led numerous combat missions in support of Operations NORTHERN WATCH, SOUTHERN WATCH, ALLIED FORCE, and IRAQI FREEDOM. Lieutenant Colonel Norton's staff assignments include Headquarters Air Forces Central, the National Guard Bureau and Headquarters United States Air Force, Strategic Plans and Programs Directorate. He holds a Bachelor of Arts degree in Political Science from Duke University and a Master of International Public Policy degree from the Johns Hopkins University's School of Advanced International Studies.

PROLOGUE

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FM COMPACOM
SUBJ: URGENT OPERATIONAL NEED FOR COUNTER-MICRO-WEAPON CAPABILITY
1. OVER THE PAST WEEK, EIGHT USAF F-35S AT KADENA AB, JAPAN, PLUS FOUR F-22S AND ONE B-2 AT ANDERSON AB, GUAM, WERE RENDERED NON-MISSION CAPABLE FOR MASSIVE AVIONICS FAILURES DURING TAXI OPERATIONS. IN EACH OF THESE AIRCRAFT, A SMALL HOLE AND INTERNAL DAMAGE WAS DISCOVERED NEAR THE COCKPIT OR RADOME. PACOM/J2 AND DIA ASSESS THE AIRCRAFT WERE ATTACKED BY A NEW MICRO-WEAPON CALLED A “SHURIKEN” (THROWING STAR). NO NATION OR GROUP HAS CLAIMED RESPONSIBILITY FOR THE ATTACKS. FORENSIC ANALYSIS YIELDED LITTLE EVIDENCE AS THE SHURIKEN SELF-DESTRUCTS AFTER IMPACT AND FUNCTION. HOWEVER, A LINKAGE TO THE RECENT HOSTILITIES NEAR THE SENKAKU ISLANDS CANNOT BE RULED OUT.
2. THE RSAF (SINGAPORE) RECENTLY COMPLETED F-15SG OT&E OF A NEW ISRAELI-BUILT ‘VAMPIRE’ POD WHICH HAS PROVEN EFFECTIVE AT DETECTING UNIQUE SIGNATURES OF THESE MICRO- WEAPONS AND DISABLING THEM DURING FLIGHT. THE RSAF HAS OFFERED TO DEPLOY A SIX-SHIP OF VAMPIRE-EQUIPPED F-15SG TO PROVIDE LIMITED DCA COVERAGE AND TO RAPIDLY INVESTIGATE SUSPECTED POINTS OF ORIGIN DETECTED BY OVERHEAD SENSORS.
3. PACOM REQUESTS THE FOLLOWING ACTIONS:
A. COORDINATE APPROVAL OF RSAF OFFER UNTIL OTHER COUNTER-MEASURES ARE IN PLACE.
B. RAPID ACQUISITION AND INTEGRATION OF VAMPIRE ONTO A-10, B-52 AND MQ-9S WHICH ARE THE ONLY USAF PLATFORMS STILL WIRED FOR EXTERNAL POD CARRIAGE [DUE TO THESE AIRCRAFT’S SLOW ACCELERATION, DCA COVERAGE AND EFFECTIVE RESPONSE TIME TO SUSPECTED LAUNCH SITES WILL REMAIN VERY LIMITED].
C. RAPID ACQUISITION AND INTEGRATION OF VAMPIRE ONTO USN F-18E/FS.

INTRODUCTION

It is not the strongest of the species that survive, nor the most intelligent, but the one most adaptive to change[1]

Plants and animals are complex systems that are highly adaptable. In fact, an organism's complexity can contribute to even greater adaptability due to greater variation in the species. [2] Through adaptation, these organisms improve their ability to survive in their environments.

While machines cannot autonomously adapt as living organism do, they can be readily modified provided that characteristic was considered and included in their design. Design theorist Josef Saleh explains that "systems that have a longer life span are the ones that are capable of coping with uncertainty and changes in their environment. Conversely, if a system is to be designed for an extended design lifetime, the ability to cope with uncertainty and changes has to be embedded in the system."[3]

As modern weapons systems have become more complex, they have often traded away their ability to adapt. In fact, the greater the complexity, the more time, cost and effort is typically required to add a new capability, integrate a new weapon, or update operational software. In other words, the more complex a weapon system is developed to be, the less adaptable it becomes. This inverse relationship between weapons system complexity and adaptability increases the risk that a disruptive innovation will render the system obsolete during

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[1] Although this quote is attributed to Darwin in many sources, including being engraved in stone on the floor of the California Academy of Science, it is most widely attributed to attorney Clarence Darrow.

[2] This paper uses "complexity" as defined by Lt Col Robert A. Dietrick in his paper, *Impact of Weapon System Complexity on Systems Acquisition*: "A measure of either actual or potential number of interactions between entities comprising the system."

[3] Joseph Saleh. *Weaving Time into System Architecture: New Perspectives on Flexibility, Spacecraft Design Lifetime, and On-Orbit Servicing*. June 2002. p.19.

its service life.[4] Such obsolescence could result from an innovation that the system is incapable of integrating or exploiting. It could also result from an innovation that the system cannot counter. This trend leaves U.S. forces more susceptible to strategic surprise or to finding themselves on the wrong side of an opposing disruptive military innovation.

This paper examines the interrelated issues of weapon system complexity and adaptability with a focus on USAF fighter aircraft force structure. It explores adaptability in fighter aircraft, comparing efforts to integrate capabilities into combat aircraft of various complexities: the integration of the AIM-9 Sidewinder on to Taiwanese F-86s during the Quemoy-Matsu crisis; the integration of the LITENING II advanced targeting pod on to the A-10A for the Iraq War; the F-22 modernization program; and the F-35 development. It explores reasons for the increasingly inverse relationship between weapon system complexity and adaptability, as well as potential solutions to reverse the trend. The paper's analysis supports the position that the USAF must take steps to ensure its future combat aircraft fleet retains sufficient adaptability to cope with the exponential rate of technological change.

THE COMPLEXITY-ADAPTABILITY PARADOX

The rate of technological change is accelerating, driven mainly by advances in information technology such as processing speed and storage capacity. [5,6] While these advances

[4] For a description of "disruptive innovations" in the defense industry, see Peter Dombrowski and Eugene Gholz. "Identifying Disruptive Innovation: Innovation Theory and the Defense Industry." *Innovations: Technology, Governance, Globalization*, Spring 2009, pp. 101-17. They define a disruptive innovation as "a technological change that introduces a product whose performance is measured in new ways."
[5] The notion of accelerating technological change has been popularized in particular by Dr. Ray Kurzweil in his books, The Age of Intelligent Machines and The Singularity is Near. He refers to it as "the law of accelerating returns."

account for many of the improvements in technology with military application in the past few decades, the accelerating rate of change in such technology increases the requirement to rapidly exploit these technological advances to maintain tactical advantage.

This accelerating pace of technological change and the diffusion of that technology through globalization have two critically important strategic effects for U.S. national security: (1) an increase in the variety and capability of adversary threats and (2) an increase in the risk of a major military innovation for which the U.S. is not prepared. The increasing severity of threats to the air domain, such as improved air defenses, is leading the U.S. Air Force into a slow, but certain, technology and cost-driven death spiral. As threats become more sophisticated, Air Force requirement writers develop increasingly complex solutions to specific tactical challenges they expect to face. The increased complexity of these new weapon systems, however, increases the time and cost to adapt them for the next phase of mission enhancement or threat response, therefore decreasing their effective adaptability.

ADAPTABILITY

Dr. Joseph Saleh provides an extensive treatment of the subject of adaptability in aircraft and spacecraft design in his MIT doctoral thesis. After an extensive literature review of the subject, Dr. Saleh defines adaptability – "flexibility" in his terms – of a design as "the property of a system that allows it to respond to changes in its initial objectives and requirements—both in terms of capabilities and attributes—occurring after the system has been fielded, i.e., is in operation, in a timely and cost-effective way."[7] This paper adopts in whole Saleh's notion of

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[6] Moore's law, named for Intel co-founder Gordon E. Moore, describes that the number of transistors that can be placed on an integrated circuit doubles every 24 months (Ethan Mollick, "Establishing Moore's Law," *IEEE Annals of History of Computing*, Jul-Sep 2006, pp. 62-75)

[7] Saleh, p.36.

“flexibility,” including the key principle of efficient and cost-effective response to change, but terms it “adaptability” because “flexibility” carries a distinct meaning to Airmen.[8]

EXAMPLES OF WEAPON SYSTEM ADAPTABILITY

The story of the first combat kill by an AIM-9 Sidewinder provides an example of very rapid integration providing a critical tactical edge. According to an internet posting by former Marine pilot “Robbie” Robbins, he and a team of five Marine aircraft maintainers deployed to Hsinchu AB, Taiwan in August 1958, during the Second Taiwan Straits Crisis over the Quemoy-Matsu islands, to integrate the newly developed AIM-9 Sidewinder missile on Taiwanese F-86Es. The Marine maintainers “in one week had milled and fitted the racks to the F86 wing and converted the HAVAR [High Velocity Aircraft Rocket] rocket system wiring with toggle switches to become a jury rigged Sidewinder tracking and firing system.” According to Robbins’ account, he conducted a live fire test from the F-86, then trained the Taiwanese pilots in its employment.[9] The following month, a Taiwanese Air Force F-86 shot down a MiG-17 in what is purportedly the first ever guided-missile aerial victory.[10]

The lead up to the 2003 Iraq War offers another example of how rapid integration of a new technology proved pivotal in combat. In 2002, word was spreading within the Air Force about the combat utility of the LITENING II advanced targeting pod (ATP), then fielded only on

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[8] According to Air Force Doctrine Document-1, flexibility “allows air and space operations to shift from one campaign objective to another, quickly and decisively”. The following article excerpt offers a useful distinction between ‘adaptability’ and ‘flexibility’: “A platform is flexible when it can satisfy a variety of potential mission requirements with a given set of capabilities, with some missions being addressed better than others; whereas adaptability is the ability to alter the package of organic mission capabilities to respond in an effective and focused way to a different threat environment or mission requirement.” Stephen M. Carmel, “Adaptability in Sea-Base Platform Design”, RUSI Defence Systems, Summer 2004, p.54.

[9] 1LT Ray “Robbie” Robbins. “323 Death Rattlers” website, a site for former members of Marine Corps‘ VMA-323 fighter squadron, http://home.inreach.com/tc/page7.html, accessed November 22, 2010.

[10] Preston Lerner, “Sidewinder-The Missile that has Rattled Enemy Pilots Since 1958,” *Smithsonian Air & Space*, November 1, 2010. See also 2nd Lt. Taylor Couch,USMC. “The Sidewinder Story” in *Centennial of Naval Aviation*. Fall 2010. Vol. 2, Issue 4. p.13.

F-16C+ aircraft in the Air National Guard and Air Force Reserve. The Air Component Commander for Central Command, General T. Michael "Buzz" Moseley, requested the formation of a 'special team' of ATP-equipped fighters to support Special Operations Forces (SOF) to secure the western desert of Iraq. The goal was to prevent the Iraqi Army from launching SCUD missiles at Israel as happened in the 1991 Persian Gulf War.[11]

Air National Guard A-10 units were also part of the 'special team' with the F-16C+ aircraft, but the A-10 lacked the ability to carry an advanced targeting pod; that capability was planned for the A-10 as part of a comprehensive "Precision Engagement" modernization set to begin in 2006. To get this critical capability on the A-10 in time for a possible invasion, the flight test pilots and engineers at the Air National Guard/Air Force Reserve Test Center (AATC), in conjunction with Northrop Grumman, developed a little black box called an Adaptive Interface Module (AIM). The AIM inserted into the launch rail from which the ATP would be suspended to connect the ATP to the aircraft. According to an AATC test pilot,

> The pod thought it was talking to a Block 30 [F-16] and the jet thought it was talking to a Maverick missile. So all we really did was create a system that intercepted the [Hands on Throttle and Stick] inputs to the Maverick and change them into LITENING speak which would modify the menus in the pod which could be displayed in the cockpit via the Maverick video lines. The unit cost was something around $30K per [Adaptive Interface Module] and was considered a throw away item. We never thought it would remain in inventory for as long as it did - which caused some issues

[11] This account is based on the author's personal experience serving on Air Forces Central (AFCENT) staff working to develop the operational concept for this 'special team'.

> since it was fielded as a [temporary modification] to support the warfighter. But at the end of the day, the battle in the western war would not have been nearly as successful, lives were saved in numerous [troops in contact] since the [A-10s] were able to be more effective and we put a targeting pod on the [A-10] when nobody said it was possible - and did it (albeit with an archaic integration) at a minuscule price.[12]

Putting an advanced targeting pod on the A-10 continued to pay huge dividends for the rest of the decade and beyond as the U.S. has waged protracted counter-insurgency campaigns in both Iraq and Afghanistan. Typical missions for F-15Es, F-16s and A-10s in these conflicts involve much more reconnaissance than weapon employment. For this reason, advanced targeting pods are typically the most important piece of mission equipment on a fighter doing close air support. This fact was magnified by the considerable adaptability and improvements of the ATPs themselves. In the past decade, ATPs have regularly added important new capabilities that optimize the sensors for the close air support role they are performing in Iraq and Afghanistan. Examples of these capabilities include video down link (VDL), multi-target tracking, and range ring symbology super-imposed on the image. [13]

INFORMATION TECHNOLOGY AND THE COMPLEXITY-ADAPTABILITY PARADOX

In both of the cases described above, the AIM-9 on the F-86 and the LITENING II ATP on the A-10, the simplicity of the aircraft's avionics architecture was instrumental in

[12] Interview with AATC Director of Operations, Lt Col Thomas "Narly" McNurlin.

[13] These advances have been assisted by a fierce competition for market share between Lockheed Martin's SNIPER and Northrop Grumman's LITENING pods. The USAF has confirmed the continued importance of the ATP and this competitive acquisition in it's recent award of the new ATP-Sensor Enhancement contract to both companies.

accomplishing the rapid integration. Such modifications are far more difficult on aircraft with complex avionics architectures. The situation is analogous to the incorporation of computers into automobiles, which increases the complexity of repairs and modifications beyond the capabilities of do-it-yourselfers. An engineering professor interviewed in a recent news article stated "The garages and the maintenance people are really at a point where repairing a car is too complex and demanding [for them]." He added that "more than 50 percent of the [electronic control units] that mechanics replace in cars are technically error free: They exhibit neither a hardware nor a software problem. Mechanics replace the [control units] simply because they don't have a better way to fix them." [14] Just as simple repairs and modifications to cars are now a thing of the past, the ability to make rapid modifications to today's software and computer system-intensive combat aircraft is likewise a victim of increased complexity. The next section will show specifically how the complexity, to include the cost, of 5th generation fighters (i.e., the F-22 and F-35) decreases their adaptability.

Not everyone, however, sees the inverse relationship between complexity and adaptability as permanent. Many believe instead that artificial intelligence can make such information technology more adaptable. The recently published *Technology Horizons* report from the USAF Chief Scientist makes frequent reference to "adaptable, autonomous systems" which could exploit "inexpensive processing power, data storage and powerful autonomous reasoning algorithms."[15] Such systems would benefit from:

> decision-making systems requiring limited or no human intervention…and future applications involving inherent decision time scales far exceeding human

[14] Robert N. Charette, "This Car Runs on Code," *Discovery News*, Feb 5, 2010. (Accessed December 11, 2010 at http://news.discovery.com/tech/toyota-recall-software-code.html)

[15] The report uses the term "adaptive" most often as part of the phrase "complex adaptive systems." However, the report offers little analysis or even definition of the terms thereby limiting its contribution to this line of inquiry.

> capacity. Technologies may include, but are not limited to, information fusion, cognitive architectures, robust statistical learning, search and optimization, automated reasoning, neural networks, complex system dynamics, and other approaches that will enable increasingly autonomous decision-making.[16]

However, while these arguments assert that enhanced complexity in weapon systems may serve to make those systems more adaptable, *Technology Horizons* appears to use the concept of "adaptability" to describe learning systems, or artificial intelligence. While it is plausible that future artificial intelligence could facilitate or enable weapon system adaptation – for example by being able to organically develop the code needed to integrate a new capability –complex information technology currently makes weapons systems less adaptable largely due to the time required to write and test software. The report expresses optimism about the prospect for developing reliable verification and validation (V&V) methods to certify the reliability that such "adaptive, autonomous" systems will perform as desired.

FIFTH GENERATION COMPLEXITY AND ADAPTABILITY

During the 1991 Persian Gulf War, television viewers marveled at video footage from F-117 Stealth Fighters over heavily-defended Baghdad showing laser-guided bombs guiding down elevator shafts. Observers have described this combination of precision and stealth as having a "revolutionary" impact on the conduct of warfare.[17] Largely in response to this Gulf War

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[16] Werner J.A. Rahm, Report on *Technology Horizons: A Vision for Air Force Science & Technology During 2010-2030*, 2010, p. 59, 100.
[17] See Michael Vickers and Robert Martinage, *The Revolution in War, Center for Strategic and Budgetary Assessment*, 2004, and Fred W. Kagan, *Finding the Target,* 2006, p.123.

success, USAF leadership decided to stop purchasing non-stealthy combat aircraft. This decision was part of a bold vision espoused by Air Force Chief of Staff Merrill McPeak to stop buying "aluminum" jets and migrate to an all "5th generation" fighter force based on the F-22 and F-35 programs.[18] Based on current program of record and projected flying rates, the only non-5th generation fighter the USAF may be operating in 2030 is one or two squadrons of A-10s. An all 5th generation fighter force, however, will lack the adaptability necessary to face the proliferating threats and national security requirements it will face in 2030 and beyond.

To enact this 5th generation force structure vision, the USAF ended "legacy" fighter procurement programs such as the F-15E and F-16C and reduced overall fighter force structure from 36 to 20 fighter wing equivalents.[19] Much of the smaller legacy force was made more capable with integration of precision weapons such as JDAM (Joint Direct Attack Munition), data links, precision targeting pods, and helmet-mounted cuing systems. The second part of this vision to transform the fighter force relied on procuring adequate numbers of F-22s and F-35s. However, the F-22 program was steadily trimmed during the 1990s and 2000s. In 2010, DOD capped further F-22 procurement at a F-22 inventory of 187. Part of the logic behind this move, along with the retirement of 250 legacy fighters, was to fund major cost growth in the F-35 program.[20]

The F-35 is currently the USAF's only manned fighter aircraft procurement program.[21] The legacy fighter fleet of A-10s, F-15s and F-16s, which fielded from the late 70s through early

[18] Grant, p. 7.
[19] The *2010 Quadrennial Defense Review* sets a USAF force structure requirement of 16-17 fighter wings (6 air superiority wings and 10-11 strike fighter wings). At 72 aircraft per wing, this equates to 1152-1224 primary mission aircraft inventory (PMAI). Total fighter inventory includes approximately 40% "overhead" of non-mission aircraft for training, test and attrition reserve.
[20] From interviews conducted with analysts in Air Force headquarters, Strategic Plans and Programs directorate.
[21] Procurement of 15 Light Attack Armed Reconnaissance aircraft is planned to begin in FY2012.

90s, will be retired over the next two decades. Therefore, by about 2030, the current plan yields a USAF fighter force of 187 F-22s, plus the number of F-35As that program eventually fields (the USAF program calls for 1763, but few expect that number to hold due to delays and cost increases).

The F-22 and F-35 offer more capability to survive in the face of vastly improved air defenses than any other manned aircraft in the world.[22] The F-22's combination of all-aspect, low-observability and high altitude super-cruise greatly reduce its vulnerability to advanced SAMs and fighters, while the integration of its advanced sensors (sensor fusion) provides very high pilot situational awareness and high fidelity targeting data. The F-35 lacks the stealth and speed of the F-22, but still has a much lower radar cross section than legacy platforms. The F-35 is also equipped with advanced infrared imaging systems for targeting and situational awareness, the Electro-Optical Targeting System (EOTS) and the Distributed Aperture System (DAS). While these 5th generation aircraft are very capable against near-term threats, they are expensive and time consuming to modify due to their complexity.

The cost and duration of the F-22 Modernization Program provide an indication of the challenge and high cost in modifying this aircraft. The program began in 2003, two years before the aircraft reached Initial Operational Capability. The first phase (Increment 2) enables supersonic employment of the Joint Direct Attack Munition (JDAM) and improves the intra-flight data link (IFDL). Increment 3.1, projected to field in FY2011, will allow Small Diameter Bomb (SDB) employment, Synthetic Aperture Radar (SAR) ground-mapping, and the ability to cue Joint Direct Attack Munitions (JDAMs) using on-board sensors. Increment 3.2, projected to

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[22] The proliferation of advanced surface to air missile systems, such as the Russian-made S-300 (SA-20), greatly complicates achieving air superiority within their tactical range. Such air defenses become even more impenetrable when combined with advanced fighters, like the new Sukhoi-35, or PAK-FA now in development, and with robust communication networks integrating active and passive sensors.

begin fielding in FY2015, will incorporate a new data link and employment of AIM-120D and AIM-9X. The total cost of the modernization is estimated at 11 billion dollars over 13 years.[23] For comparison, the United Arab Emirates purchased 80 new, highly advanced F-16E/F aircraft for just $6.4 billion in a deal that included bed down, training and maintenance services.

A cost comparison of F-16 and F-22 software modification further reveals F-22 adaptability issues. Many of the upgrades listed above, such AIM-9X and sensor-cued JDAM employment, have already been integrated on U.S. F-16C/Ds, and at a significantly lower cost than the F-22 integration. Table 5 compares annual F-16 and F-22 Research, Development, Test and Evaluation (RDT&E) budget projections which fund regular updates to these aircraft's Operational Flight Programs (OFPs) to incorporate new capabilities or required changes to the mission software. Much of this RDT&E funding simply pays for software engineers to write and test code. While not a precise comparison of like capability integration, this table reveals the challenge of modifying complex avionics like the F-22's.

In addition to the higher cost, the time required to integrate and field each new capability is considerably longer for the F-22 than for the F-16. In many cases, the F-16 has fielded the capability well before the F-22 due to simpler integration requirements. Therefore, comparing total cost per specific new capability yields an even larger difference than the annualized cost ratio displayed in Table 5. This comparison of modernization costs demonstrates the greater adaptability of legacy platforms over more complex, fifth generation aircraft.

$M	FY09	FY10	FY11	FY12	FY13	FY14	FY15

[23] Senate Report 111-29, Department Of Defense Appropriations Bill 2011, September 16, 2010.

F-16 RDT&E	123.7	142.6	129.1	129.1	112.6	109.1	110.7
F-22 RDT&E	579.9	569.3	576.3	555.2	467.9	454.0	677.4

Table 1: F-16 and F-22 RDT&E Budget Projections (Fiscal Year 2011)[24]

As the F-35 is not yet fielded, we lack the steady state data on cost and time to update OFP or modernization efforts. However, the cost and complexity of the F-35 software effort does offer a hint as to its future adaptability. The challenge of developing software for the F-35 has been a major source of the delays and cost increases in that program. According to a March 2010 report by the Government Accounting Office (GAO), "The JSF [F-35] software development effort is one of the largest and most complex in DOD history, essential to providing capabilities for sensor fusion, weapons and fire control, diagnostics, and propulsion." The report explains that just since 2007 the expected completion date for the OFP that will provide full mission capability has slipped from 2012 to 2015.[25] Shortly after the GAO report was published, DOD slipped the program an additional year to 2016.

The GAO report predicted that software-driven delays are likely to continue. Currently, "JSF engineers have written about three-fourths of the total lines of aircraft code expected and about 40 percent of the written code has been integrated and tested. This is typically the most challenging phase of software development." The report states the aircraft OFP currently has over 18 million lines of software code, but that an independent DOD Joint Estimating Team (JET) predicts that will continue to grow. (By comparison, the F-22 has 2.2 million lines of software code and the F-18E/F has 1.1 million.) The JET noted that "JSF software has grown 40

[24] Air Force Budget Item Justification submitted to Congress in February 2010 as part of the Fiscal Year 2011 President's Budget Proposal
[25] Government Accountability Office. *Joint Strike Fighter: Additional Costs and Delays Risk Not Meeting Warfighter Requirements on Time*. March 2010, p.26.

percent since the preliminary design review," but that "the most complex and troublesome work is still ahead."[26] These examples clearly demonstrate how increased size and complexity of mission software reduces weapon system adaptability.

A closely related factor impacting adaptability is sensor fusion, which is unique to the F-22 and F-35.[27] This feature of 5th generation aircraft directly increases the complexity of avionics architecture by integrating all the major systems. Such an integrated system requires extensive regression testing to ensure that changes to one component don't adversely impact other components. Sensor fusion likely contributes significantly to 5th generation aircraft's lack of adaptability.

A second potential reason for the time and cost associated with complex aircraft software could be related to DoD organizational factors. In Affording Defense, Dr. Jacques Gansler points out that while weapon system development timelines have increased in proportion to system complexity, DoD development timelines are nevertheless considerably longer than those for commercial systems of comparable complexity.[28] Returning to our comparison to the auto industry, a premium car, such as a new high end Mercedes, may have five times as many

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[26] Ibid.
[27] Sensor fusion is "the process of collecting data, combining those data through a variety of methods, with a variety of sensing technologies, and presenting those data as an integrated product to a machine or a human." In these fighters, it reduces pilot workload by integrating the data (primarily ELINT, or electronic intelligence) collected by on-board and off-board sensors and presenting it on a single display. The explosion in data available from on-board and off-board sources can easily exceed the pilot's ability to process it. Reducing pilot workload provides a tactical advantage in a dynamic battle space by allowing more time for the pilot to process information, make decisions, communicate, and employ weapons. By comparing and combining inputs from multiple sensors, sensor fusion also provides more accurate target information and situational awareness to the pilot. It is a very useful feature for improving combat performance in dynamic, high threat environments. Due to its impact on avionics software complexity, this capability does appear to come at a price to weapon system adaptability.
[28] Jacques Gansler, *Affording Defense*, p.172.

software lines of code as an F-35.[29] A comparative analysis of productivity between software acquisition and development processes in the two industries may provide useful insights.

RECOMMENDATIONS

Our strategy, forged in war, is focused on fielding modular, adaptive, general purpose forces that can be employed in the full range of military operations.

- The National Military Strategy of the United States of America, February 2011

So what can be done now to avoid a future in which the US Air Force is saddled with a force structure that lacks the adaptability to keep up with the pace of technological change? This paper offers two recommendations:

1. Incorporate "adaptability" as a performance requirement in future procurement efforts, and

2. Streamline the acquisition of mission software,

ADAPTABILITY AS A REQUIREMENT

The challenges posed by threats such as advanced Anti-Access/Area Denial systems encourage Air Force planners to "require" the most advanced capabilities that the defense industry can promise. Such high end requirements lead to the pursuit of ever more complex

[29] Robert N. Charette, "This Car Runs on Code," *Discovery News*, Feb 5, 2010, (Accessed December 11, 2010 at http://news.discovery.com/tech/toyota-recall-software-code.html)

weapon systems. As demonstrated in this paper, such complexity can reduce adaptability in Air Force capabilities and thereby create an “Achilles Heel” of rigidity that can and will be exploited by adversaries at the high and low ends of the conflict spectrum. To counter this rigidity, requirements for new Air Force weapons systems should begin with more modest, less complex initial capabilities but include capacity to support future modifications though block upgrades. Design approaches based on open system architectures could provide this greater capacity for adaptability.

Incorporating greater adaptability into a weapon system’s design can do more to ensure operational availability decades in the future than meeting certain specific capability requirements. The current requirements process presumes that requirements writers can accurately predict the military capabilities that will be required during the expected life span of the weapon system decades in the future. However, as design-to-fielding timelines steadily increase, and required aircraft service life extends (largely due to the increasing cost of recapitalization), capability ‘requirements’ for conflicts many decades in the future become mere guesses. As explained above, the accelerating change in technology exacerbates this trend considerably.

Senior Defense Department leadership expressed sentiments in line with this recommendation when they unveiled plans for a new long-range bomber program as part of the fiscal year 2012 defense budget submission. Apart from stating the bomber will be nuclear-capable, stealthy and optionally-manned, most specific program requirements have not been released. Nevertheless, Defense Secretary Gates insisted that the bomber “will be designed and

developed using proven technologies."[30] Air Force Chief of Staff Schwartz added "we're not going to be as ambitious as we perhaps were at one time."[31] The chairman of the Defense Science Board, Paul Kaminski, endorsed "using an incremental block approach to adding new capabilities" to the new bomber.

Such an approach would involve an open systems architecture that would simplify the integration of new technologies after aircraft fielding. [32] This open architecture approach is described in a February 2011 Defense Science Board report entitled "Enhancing Adaptability of US Military Forces." According to this report, "If long-term operation and evolving mission needs are expected, the investment in an open architecture system will pay off many times over in the long run."[33] Long term operation and evolving mission needs certainly describes the present and future of complex combat aircraft. A thorough explanation of the characteristics of open system architectures is found in Table 2.

[30] Secretary of Defense Robert Gates, *Statement on Budget and Efficiencies*, January 6, 2011, http://www.defense.gov/speeches/speech.aspx?speechid=1527.
[31] Dave Majumdar, "Air Force Scaled Back Vision for New Bomber," *Air Force Times*, February 9, 2011 accessed 2-11-2011 at http://www.airforcetimes.com/news/2011/02/defense-schwartz-bomber-plans-020911/.
[32] Ibid.
[33] Al Grasso and Dr. William LaPlante, *Defense Science Board 2010 Summer Study on Enhancing Adaptability of US Military Forces*, p.66.

Characteristic	Open System	Remarks
Decouple hardware and software	Hardware and software can be changed independently of each other	Decoupled hardware and software enables the owner of the system to easily upgrade the hardware and software.
Decoupled software modules	Software components have modularity defined functionality	Defined modular functionality allows the owner of the system to quickly introduce new capabilities.
Defined data model	Data contents and meaning defined and published in a model.	Defined data models simplify the process for adding new capabilities into the system.
Interface definition	The hallmark of an open system is the definition of the various interfaces of the system.	Open systems only work if their interfaces are defined and available. Interface should be non-proprietary and owned by the customer.
Standards	Use government or industry defined and controlled standards.	Choosing the correct set of standards is highly dependent upon the environment in which the system operates.
Life cycle development models	Can use any life cycle development model – works best with iterative and evolutionary models	System owners benefit when using iterative and evolutionary models with open architecture systems.
COTS	Embrace COTS and are designed to support the dynamic aspects of using COTS.	Open architecture systems are designed to leverage the tremendous power associated with tapping in the COTS computing world and bringing newer technologies to the field faster.
Data rights	Buyers of the system have the rights necessary to maintain the system.	Open architecture systems do not have data rights, which makes it difficult to add new capabilities.

Table 2: Characteristics of Open Architectures[34]

[34] Ibid, p. 61.

STREAMLINE THE ACQUISITION OF MISSION SOFTWARE

The Department of Defense reported to Congress in November 2010 on its progress on a new initiative to streamline the acquisition of information technology. The rationale for this initiative is because, according to the Defense Science Board, the DoD is "struggling to keep pace with the speed at which new IT capabilities are being introduced in today's information age—and the speed at which potential adversaries can procure, adapt, and employ these same capabilities against the United States."[35] According to the DOD report, "the new process for delivering IT capability will differ significantly from the traditional weapon system development acquisition process." For example, "information capabilities will be delivered as a series of short-duration projects that deliver incremental capabilities in shorter timeframes." In addition, "a modular open system approach will be applied to foster open architecture, enable the widest selection of vendor options for ease of upgrades, and encourage competition throughout the lifecycle."[36]

The new process will not apply to acquisition of IT "embedded in weapon systems," but upgrades to embedded IT software "may be considered when no hardware change is required."[37] It remains to be seen whether this initiative will have an impact and the extent to which it improves weapon system adaptability. There may also be downsides to the competitive sourcing of upgrades due to the possibility of having to coordinate software updates with multiple software vendors for their pieces of the OFP.

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[35] Department of Defense Report to Congress (Pursuant to Section 804 of the FY10 NDAA), *A New Approach for Developing Information Technology Capabilities in the Department of Defense*, November 2010, p.3,9.
[36] DOD Report, p.9-10.
[37] DOD Report, p. 18.

The United States Air Force’s critical role in securing the commons, preserving regional stability and protecting US interests demands that it maintain a technological advantage over current and potential adversaries. However, it is getting more difficult to predict the nature of the technologies available to exploit or face in battle. As it pursues ever more complex weapon systems and capabilities, the USAF combat force structure must retain the ability to quickly adapt to disruptive military innovations and significant changes in the threat environment.

Bibliography

Air Force Doctrine Document 1. *Air Force Basic Doctrine*. 17 November 2003.

Carmel, Stephen M. "Adaptability in Sea-Base Platform Design." *RUSI Defence Systems* Summer (2004). Web. 12 Feb. 2011. <http://www.rusi.org/downloads/assets/Carmel.pdf>.

Couch, Taylor, 2nd Lt, USMC. “The Sidewinder Story.” *Centennial of Naval Aviation* Fall 2010. Vol. 2, Issue 4.

Charette, Robert N. “This Car Runs on Code.” *Discovery News*. 5 Feb, 2010. Web. 11 Dec. 2010. < http://news.discovery.com/tech/toyota-recall-software-code.html>.

Dietrick, Robert A. "Impact of Weapon System Complexity on Systems." Thesis. Air Command and Staff College, 2006. Print.

Dombrowski, Peter, and Eugene Gholz. "Identifying Disruptive Innovation: Innovation Theory and the Defense Industry." *Innovations: Technology, Governance, Globalization* 4.2 (2009): 101-17. Web. 14 Feb.2011. <http://web.mit.edu/ssp/people/gholz/INNOVATIONS-4-2_dombrowski-gholz.pdf>

Gansler, Jacques S. *Affording Defense*. Cambridge, MA: MIT, 1989. Print.

Gates, Robert. "Statement of Budget and Efficiencies." Speech. Washington, D.C. 6 Jan. 2011. Web. 11 Feb. 2011. <http://www.defense.gov/speeches/speech.aspx?speechid=1527.>.

Grant, Rebecca. *Losing Air Dominance*. [Arlington, VA]: Mitchell Institute, 2008. Print.

Grasso, Al, and William LaPlante. *Report of the Defense Science Board Summer Study on Enhancing Adaptability of U.S. Military Forces*. Washington, D.C.: Office of the Undersecretary of Defense for Acquisition, Technology, and Logistics, 2011. Print.

Kagan, Frederick W. *Finding the Target: the Transformation of American Military Policy*. New York: Encounter, 2006. Print.

Kurzweil, Ray. *The Singularity Is Near: When Humans Transcend Biology*. New York: Viking, 2005. Print.

Kurzweil, Raymond. *Age of Intelligent Machines*. Cambridge: MIT, 1992. Print.

Lerner, Preston "Sidewinder-The Missile that has Rattled Enemy Pilots Since 1958." *Smithsonian Air & Space*. November 1, 2010.

Mollick, E. "Establishing Moore's Law." *IEEE Annals of the History of Computing* 28.3 (2006): 62-75. Print.

Robbins, Ray. *323 Death Rattlers*. Web. 14 Feb. 2011. A site for former members of Marine Corps VMA-323 fighter squadron

S. Rep. No. 111-29 (2010). Print.

Saleh, Joseph. *Weaving Time into System Architecture: New Perspectives on Flexibility, Spacecraft Design Lifetime, and On-Orbit Servicing*. Thesis. Cambridge: MIT, 2002. Print.

"Timeline for the P-51 Mustang." *Military History Encyclopedia on the Web*. Web. 15 Feb. 2011. <http://www.historyofwar.org/articles/weapons_P-51_timeline.html>.

United States. Air Force. Chief Scientist. *Report on Technology Horizons: A Vision for Air Force Science & Technology During 2010-2030*. By Werner JA Dahm. Washington, D.C., 2010. Print.

United States. Dept. of Defense. *Quadrennial Defense Review Report*. Washington, DC: Secretary of Defense, 2010. Print.

United States. Government Accountability Office. *Joint Strike Fighter: Additional Costs and Delays Risk Not Meeting Warfighter Requirements on Time.* Web. 14 Feb. 2011. <http://www.gao.gov/products/GAO-10-382>.

"USAF Scaled Back Vision for New Bomber." *DefenseNews.com.* 9 Feb. 2011. Web. 15 Feb. 2011. <http://www.defensenews.com/story.php?i=5665221&c=AIR&s=TOP>.

Vickers, Michael G., and Robert C. Martinage. *The Revolution in War*. Washington, DC: Center for Strategic and Budgetary Assessments, 2004. Print.